The EXOSAT data on GX 339–4: further evidence for an "intermediate" state

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ABSTRACT

We have studied the fast timing and spectral behavior of the black hole candidate (BHC) GX 339–4 using all 1–20 keV *EXOSAT* ME data: the July 1983, March 1984, May 1984 and April 1985 observations. In April 1985 GX 339–4 was in a weak low state (0.03 10^{-9} erg cm^{-2}s^{-1}, 2–10 keV). The X-ray spectrum was a hard power law with a photon index α of 1.82 and the power spectrum, though ill-constrained by the data, was consistent with a typical BHC low state spectrum. During the other three pointings the system was brighter (1.5 10^{-9} erg cm^{-2}s^{-1}, 2–10 keV), an ultrasoft component was present in the spectrum, and the power law was steeper (α ~3.5 in 1984; in 1983 it was not well-measured); the power spectrum showed a flat-topped band-limited noise component with a break frequency of ~4.5 Hz and a fractional rms amplitude of ~7%. Comparing flux levels, X-ray spectra and power spectra we conclude that in these observations GX 339–4 was in a state intermediate between the usual BHC low and high states. The system was ~ 4 times brighter than in its usual low state, 4 times fainter than in its usual high state, and an order of magnitude fainter than in its very high state. We compare these results to those recently obtained on other BHCs, and conclude that this "intermediate state" behavior is a common characteristic of BHCs, that occurs at $\dot{M}$ levels intermediate between the high and the low state. We argue that this result can be used to resolve the long-standing issue of the dependence of the power spectral break frequency in the low state on mass accretion rate, and strengthens the idea that low-state noise and very-high state noise may have a common origin. We briefly discuss a possible interpretation for the changes in break frequency in the low state and between low state and intermediate state.

Subject headings: – Black hole physics – Stars: binaries: close – Stars: individual: GX 339–4 – X-Rays: stars

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1. Introduction

Discovered with the OSO–7 satellite (Markert et al. 1973), GX 339–4 is considered a black hole candidate (BHC) due to the characteristics of its fast X-ray variability, and high-low (soft-hard) state transitions similar to Cyg X–1. Its X-ray behavior has been studied with various satellites (Markert et al. 1973, Samimi et al. 1979, Nolan et al. 1982, Motch et al. 1983, Ricketts 1983, Maejima et al. 1984, Makishima et al. 1986, Ilovaisky et al. 1986, Miyamoto et al. 1991 and 1992). The source has shown large random variability on time-scales of milliseconds up to months (Markert et al. 1973, Samimi et al. 1979, Motch, Ilovaisky, & Chevalier 1982, Motch et al. 1983), and quasi-periodic oscillations (QPOs) have been reported with frequencies of ~ 6.25 Hz (Makishima et al. 1988), ~ 0.8 Hz (Grebenev et al. 1991), ~ 0.1 Hz (Motch et al. 1983, Motch et al. 1985, Imamura et al. 1990) and ~ 0.05 Hz (Motch et al. 1983). The optical counterpart of GX 339–4, a star of V ~ 18 mag. discovered by Doxsey et al. (1979), was also searched for fast variability and QPOs (e.g., Motch et al. 1983, Motch et al. 1985), and in some cases the results were similar to X-ray data obtained simultaneously. Optical periodicities of 1.13 ms (Imamura et al. 1987) and 190 s (Steiman-Cameron et al. 1990) were reported, however these results have not been confirmed. Finally, photometric data revealed a 14.8-h modulation of the brightness of the optical counterpart (Callanan et al. 1992), which may be the orbital period of the system.

Despite the fact that the compact object mass has not been measured, GX 339–4 is a prototype BHC in that it has shown all three of the classical black hole "states" (see van der Klis 1995 for a review): (1) the low state (LS), with a flat (α=1.5–2) power law X-ray spectrum (Tananbaum et al. 1972) and strong (25–50% rms) band limited noise (Oda et al. 1972) with a break frequency of 0.03–0.3 Hz; (2) a high state (HS) where the $2-10$ keV flux is an order of magnitude higher than in the LS due to the presence of an ultrasoft X-ray spectral component with sometimes an α=2–3 power law tail, and a weak (few % rms) flat power law power spectrum; and (3) a very high state (VHS; Miyamoto et al. 1991) characterized by high X-ray luminosity (2–8 times higher than in the HS), an ultrasoft X-ray spectral component plus a ($\alpha \sim$2.5) power law tail, strongly variable 1–15% rms band limited noise with a much higher cut off frequency (1–10 Hz) than in the LS, and 3–10 Hz QPO. The 2–10 keV flux is higher in the HS than in the LS, but at higher energies the situation is often the reverse, and in some sources, (e.g., GX 339–4; Grebenev et al. 1993) the integrated 1–200 keV luminosity is higher in the LS than in the HS. The order in which black hole transients have been observed in their decay to go through these states, and also similarities to neutron star states strongly suggest, however, that the accretion rate is highest in the VHS, lower in the HS and lowest in the LS (van der Klis 1994). As noted by van der Klis (1995), there is some ambiguity in the way the HS has been defined. When only spectral data and no time variability data were available, the HS was loosely defined as any state where the ultrasoft component was not negligible compared to the power law component in the 2–10 keV range. When the variability was also measured, it turned out that the HS was also characterized by an absence of band-limited noise such as in the LS; any band limited noise in the HS was thought to be a characteristic of the power law X-ray spectral component and therefore stronger at higher photon energy (Oda et al. 1976, Miyamoto 1994), so this absence of band-limited noise, as observed, for example, in the HS of GS 1124–68 was also used as a HS criterion. Of course, for the observations classified as HS with no variability information, we can not be sure of the noise properties.

A characteristic property of the LS band-limited noise is its variable break frequency; the power spectrum above the break changes very lit-

Table 1

Observations of GX 339–4 carried out with *EXOSAT*.

Start Date, UT	End Date, UT	OBC modes	Time resolution[a] [1/1024 s]	Count rate [c/s]	Nr. of detectors on source	Detector I.D.
1983 Jul 17, 01:40	1983 Jul 17, 06:44	HER4, HTR3	8	888.4	4	Ar + Xe
1984 Mar 12, 09:47	1984 Mar 12, 16:10	HER5, HTR3	8	270.2	4	Ar
1984 May 4, 04:15	1984 May 4, 10:26	HER5, HTR3	8	296.2	4	Ar
1985 Apr 29, 11:54	1985 Apr 29, 17:56	HER4/6, HTR3	32	612.8	4	Ar + Xe

[a]HTR3 mode

tle, whereas below the break the power spectrum is approximately flat and power is "missing" from the power spectrum (Belloni & Hasinger 1990a, Miyamoto et al. 1992). These break frequency variations, which anticorrelate with the level of the flat top take place without any correlation with the 2–20 keV flux (Belloni & Hasinger 1990a) or X-ray spectrum (van der Klis 1994), but there is a correlation with the 40–145 keV spectral properties (Crary et al. 1996). On the basis of the similarities between LS and VHS noise, and similarities with neutron star phenomenology, van der Klis (1994) suggested that the break frequency increases with mass accretion rate.

GX 339–4 seemed to fit right in with this picture (Ilovaisky et al. 1986, Nolan et al. 1982, Miyamoto et al. 1991). In what follows we analyze all *EXOSAT* ME data on GX 339–4 and study the relation between the X-ray spectrum and the power spectrum. This work was motivated by the peculiar characteristics (high break frequency and low rms at an intermediate X-ray flux) of the power spectrum of this source presented by Belloni & Hasinger (1990b). (A similar situation existed with the 1991 May 17, power spectrum of GS 1124–68 presented by Miyamoto et al. 1994; see Belloni et al. 1996a for a report on the power spectral characteristics of that source). Although some of the *EXOSAT* data of GX 339–4 have been reported previously (Ilovaisky et al. 1986 discussed the X-ray spectra of May 1984 and April 1985, while Belloni & Hasinger 1990b published the power spectra of July 1983 and March 1984), in none of these papers a full comparison of timing and spectral data was performed. As we will argue in Section 4, when viewed in the light of our current understanding of black-hole candidate phenomenology, the EXOSAT data on GX 339–4 provide new insight into the nature of the transition between low and high state in black hole candidates.

2. Observations and data reduction

The Medium-Energy (ME) experiment on board *EXOSAT* consisted of an array of eight detectors (each with an argon and a xenon-filled proportional counter) with a total area of 1600 cm^2 that gave moderate spectral resolution in the 1–50 keV band (Turner, Smith, & Zimmermann 1981, White & Peacock 1988). The experiment was divided in two halves, each consisting of four detectors. In our observations, one half was pointed at the source and the other half was offset to measure the background. Sometimes "array swaps" were performed where the two halves switched role. Data were processed by an On Board Computer (OBC) which had different modes emphasizing either spectral (HER, High Energy Resolution) or timing (HTR, High Time Resolution)

Table 2
Lorentzian fitting to the power spectra of GX 339–4.

Date	rms [%]	HWHM [Hz]	Reduced χ^2
Jul 83	6.9 ± 1.2	5.0 ± 2.6	0.90
Mar 84	7.5 ± 0.5	3.9 ± 0.6	1.03
May 84	6.6 ± 0.6	5.2 ± 1.5	0.95
Apr 85	< 26	–	–

information. GX 339–4 was observed four times with this instrument. A log of the observations is given in Table 1. The OBC programs used for the data presented here were HTR3, HER4 and HER5. For the spectral studies we used the HER data from the 1–20 keV argon detectors. For the timing studies we used the HTR3 data. In this mode counts detected by both halves, aligned and offset, were accumulated without energy information. HTR3 count rates sometimes include only the argon detectors, and sometimes both argon and 5–50 keV xenon detectors summed together (see Table 1). The xenon detectors contributed mainly background.

2.1. Timing data

To study the timing behavior we divided the data into segments of 8192 contiguous bins, preserving the full time resolution Δt available in each case (see Table 1). Each segment was checked for gaps and spikes (due to instrumental effects), where a spike was defined as a single-bin excess over the average count rate with a probability of occurrence from Poisson statistics of $< 10^{-8}$ per bin. Data segments with a spike or a gap (only a few percent in each observation) were excluded from further analysis. We produced power spectra by Fourier transforming each segment, and squaring and Leahy-normalizing the resulting Fourier transforms. Our power spectra thus span from $(8192\Delta t)^{-1}$ to $(2\Delta t)^{-1}$ Hz. We subtracted the deadtime affected Poisson noise (Kuulkers et al. 1994) and the instrumental high-frequency noise (Berger and van der Klis 1994) individually from each power spectrum, and then averaged the corrected power spectra (see van der Klis 1989). We finally renormalized the average power spectra to (rms/mean)^2/Hz normalization (e.g., van der Klis 1995), logarithmically rebinned them and fitted them using power laws, Lorentzians and various combinations of these functions.

2.2. Spectral data

We extracted and background subtracted the HER spectra using the *EXOSAT* Interactive Analysis (IA) software (Parmar, Lammers, & Angelini 1995). For the April 1985 data the background was determined from the same detectors as used for recording the source spectrum, using an array swap. We corrected for the small differences due to detector tilt ("difference spectra"; Parmar et al., 1995). For the March and May 1984 data no array swap was performed, so slew data were used instead to obtain a background estimate. We carefully examined these for possible variations, and excluded times when the background was unstable. During the July 1983 observation neither method could be applied, and the spectrum obtained was of bad quality, so it was not

Table 3

X-ray spectra of GX 339–4.

Date	N_H [10^{22} cm^{-2}]	kT [keV]	n (photon-index)	Flux[a][erg cm^{-2} s^{-1}]	Reduced χ^2
Mar 84	0.78 (0.68 – 0.89)	0.42 (0.41 – 0.43)	3.74 (3.57 – 3.89)	1.51×10^{-9}	1.15
May 84	0.55 (0.46 – 0.65)	0.42 (0.41 – 0.43)	3.17 (2.97 – 3.36)	1.50×10^{-9}	0.83
Apr 85	0.51 (0.33 – 0.82)	–	1.82 (1.64 – 2.02)	3.10×10^{-11}	1.11

[a]Unabsorbed total flux in the 2–10 keV range.

3σ confidence ranges are indicated in brackets.

used in our further analysis. All reduced spectra were compared to those available from the archives at the High Energy Astrophysics Science Archive Research Center (HEASARC) in Goddard, and the agreement was excellent.

3. Results

3.1. Power spectra

All but the 1985 power spectra showed a band limited noise component with an approximately flat top extending up to 2–4 Hz that gradually steepened towards higher frequencies, with no noticeable peaks. In all three cases a good fit was attained using a single zero-centered Lorentzian (a broken power law fitted as well), with a HWHM (half-width at half maximum) of about 4.5 Hz and a root mean square variability (rms) of about 7% (0.001–60 Hz). The best fit parameters are given in Table 2. The power spectrum of April 1985 was ill-constrained, as the source count rate was quite low. The 3σ upper limit to the 0.002–10 Hz power corresponded to an rms amplitude of 26%. All power spectra are shown in Fig. 1.

3.2. X-ray spectra

We fitted the X-ray spectra with the sum of a blackbody and a power law function to represent the ultra-soft and the hard component, respectively, plus interstellar absorption. This choice does not mean that we argue in favor of such a model over physically motivated models. However, the model provides a good fit to our data and its simplicity allows us to easily analyze the relative importance of each component as a function of source state.

As the ME experiment was not sensitive to low absorption columns, we made a simultaneous fit to the ME and Low-Energy (LE) data available for the 1984 and 1985 observations. In 1984 LE data were taken using the 3000 lexan, the aluminium/parylene and the boron filters, each of them with different spectral responses. In 1985 only the 3000 lexan filter was used.

The best fit parameters are given in Table 3, and the spectra are shown in Fig. 2. The slopes of the fitted power laws of the March and May 1984 spectra are significantly different, but both much steeper ($\alpha \sim$3.5) than that of April 85 ($\sim$1.8). In April 1985 no soft component is detected (this was already noted by Ilovaisky et al. 1986).

Almost in all cases the absorption in the line of sight is in accordance, within the quoted error bars, to the value of $N_{\rm H} = (5.0 \pm 0.7)\ 10^{21}$ cm^{-2} obtained by Ilovaisky et al. (1986).

Table 4

Parameters for the four different states in BHC's.

	GX 339–4				Cyg X–1 [a]			GS 1124–68			
	LS	IS	HS	VHS	LS	IS	HS [b]	LS	IS	HS	VHS
Flux $(2-10$ keV$)$ [c]	1	4	19	54	1	3	5	1	6	35	248
n (photon index)	1.6	3.5	2.0	2.5	1.5	2.2	2.7	1.6	2.3	2.4	2.3
rms [%]	18	7	< 2	10	30	20	$\cdots$	20	6	< 1	8
$\nu_{\rm cut}$ [Hz]	< 1	5	0 [d]	2	< 1	5	$\cdots$	0.2	3	0 [d]	2

Note.—All values quoted are approximate values.

[a]Cyg X–1 was never observed in the VHS.

[b]No published power spectrum of Cyg X–1 in the HS. In view of the lack of timing data, the 2–10 keV flux suggests that previously reported Cyg X–1 HS observations may also be interpreted as IS.

[c]In units of the flux in the LS. The LS fluxes of GX 339–4, Cyg X–1 and GS 1124–68 are 0.4, 7.1 and 0.8 10^{-9} erg cm^{-2} sec^{-1} respectively.

[d]Power spectrum is a power law.

References.— GX 339–4: Maejima et al. 1984; Makishima et al. 1986; Grebenev et al. 1991; Miyamoto et al. 1991; Iga et al. 1992; this paper; Cyg X–1: Ogawara et al. 1982; Belloni et al. 1996b; GS 1124–68: Miyamoto et al. 1994.

4. Discussion

Our analysis indicates that in April 1985 GX 339–4 was probably in a weak LS. Although this was usually called 'off state' because the 2–10 keV flux is ~10 times lower than in the LS, the ratio of the X-ray to optical luminosity (Motch et al. 1985), the energy spectrum (compare Table 3 of this paper to Table 1 in Iga, Miyamoto, & Kitamoto 1992) and the total rms (upper limit, Table 2) are consistent with that of a typical BHC low state. More sensitive timing data would be necessary to determine if this is in fact a different state, or just a LS at a lower mass accretion rate. However, the July 1983, March and May 1984 observations do not fit in with any of the classical BHC states discussed in Section 1. The presence of an ultrasoft X-ray spectral component, the steepness of the power law X-ray spectral component and the weakness and high break frequency of the band-limited noise make these observations very different from the LS. The presence of the band limited noise shows that the source was not in the HS. The X-ray spectral and power spectral characteristics seem to be most similar to a VHS, but the total 2–10 keV flux is an order of magnitude lower than that in the VHS (Miyamoto 1991), and in fact *in between* previously reported LS (Iga et al. 1992) and HS (Makishima et al. 1986) levels, a factor ~4 away from each.

Although it was not possible to analyze the energy spectrum of the July 1983 data, the flux level and the characteristics of the power spectrum were similar to the 1984 observations, suggesting that then the system was in a similar state.

GX 339–4 in these observations seems to have been in a similar state to that which GS 1124–68 showed on 1991 May 17, with a flux intermediate between the LS and the HS, an X-ray spectrum consisting of an ultrasoft component and a power law tail (Ebisawa et al. 1994), and a power spectrum similar to that of the VHS with a break frequency of a few Hz (Miyamoto et al. 1994). A 6 % rms QPO at 6.7 Hz was recently discovered in GS 1124–68 in this state (Belloni et al. 1996a). The lower count rates would have prevented us from detecting a similar feature in GX 339–4 if it had been present. As its X-ray flux decayed, GS 1124–68 subsequently went through the VHS, HS, and LS (Miyamoto et al. 1993), demonstrating the connection between source state and mass accretion rate; the May 17 observation also in time occurred in between the HS and the LS.

Based on this comparison we conclude that during July 1983 and March and May 1984 GX 339–4 was also in a state intermediate between the LS and HS. We will refer to this state as Intermediate State (IS). It is characterized by a 2–10 keV flux intermediate between LS and HS, a two component energy spectrum (consisting of a soft component and a power law), and a band-limited power spectrum that is flat up to a few Hz, and then decays at higher frequencies. In Table 4 we compare the general properties of the different states in GX 339–4, and in two other BHC's, Cyg X–1 and GS 1124–68. From this Table it can be seen that in all cases the IS flux is in between that in the LS and that in the HS (and thus much lower than in the VHS). The IS cut-off frequency is always much higher (and the rms lower) than in the LS, and in all three cases the energy spectrum is softer in the IS than in the LS. However we note that the power law slope in GX 339–4 (3.5) is different from that in Cyg X–1 and GS 1124–68 (2.2–2.3). Due to the narrow spectral coverage, the actual value of the power law slope in GX 339–4 depended upon the model adopted for the soft component, ranging from ~ 2.2 for an unsaturated Comptonized spectrum, to ~ 3.5 for a blackbody spectrum. Nevertheless it must be stressed that a power law was always needed, and that no good fit to the data was possible by means of a single component model. Except for the flux, which is $\sim 10-40$ times lower, the timing and spectral parameters in the IS are similar to those in the VHS. Although this may lead to interpret the IS as a weak VHS, this explanation

should also account for the existence of a HS in between.

On the basis of a comparison of the anticorrelation between break frequency and power density at the break observed in Cyg X-1 (Belloni & Hasinger 1990a) and the values of these two parameters in the VHS of GX 339–4 and GS 1124–68, van der Klis (1994) proposed that the noise in these two states might follow the same relation of break-frequency vs. power-density at the break, and are perhaps due to the same physical process. The intermediate state observations in GX 339–4 and GS 1124–68 fit in with the VHS results (Fig 3), and by their closer association with the LS (closer in flux in both sources, and also in time sequence in GS 1124–68), strengthen this idea. The implication of this of course is, that there exists a correlation with mass accretion rate, where the break frequency increases and the rms decreases as the accretion rate increases (see also van der Klis 1994), which would resolve the long-standing issue of the dependence of the break frequency on mass accretion rate in the LS. The problem with that interpretation is the absence of systematic 1–20 keV X-ray spectral variations in the LS which would indicate a systematic change in accretion rate with break frequency. However, the recent results of Crary et al. (1996) show that there *is* a correlation with the 45–140 keV X-ray spectral properties, a steeper power law index and lower flux correlating with a higher break frequency. We note, that extrapolating the Crary et al. results to lower energy, the spectra are seen to pivot around a point near 40 keV (van der Klis 1996), so that on that basis one would expect a positive correlation between break frequency and 2–10 keV count rate. Of course, this is not observed, perhaps due to the presence of a weak variable ultrasoft component even in the LS. Our proposed interpretation of a positive correlation between break frequency and accretion rate in the LS and IS would imply that the 45–140 keV flux drops and its slope steepens when the accretion rate increases. This is similar to what is already known to be the case in the LS to HS transitions.

Finally, we consider the relation between break frequency vs. power at the break among all black hole candidates. The power spectra of many black hole candidates show various bumps and wiggles, and even clear QPO peaks (e.g., van der Hooft et al. 1996) at frequencies around the break frequency. We point out that in spite of these complications, it is still possible to define the width, or the break frequency of such power spectra, for example by extrapolating the high and low frequency parts of the power spectrum to where they intersect (the method we used), or by fitting a broad smooth shape and ignoring the residual peaks. Using this approach, we have collected the relevant data on all black hole candidate power spectra in the LS, IS and VHS, and plotted them in Fig 3. Clearly, there is a trend that is common among all black hole candidates towards higher break frequency corresponding to lower power density at the break.

We point out, that in some models (e.g., Narayan 1996), the inner radius of the accretion disk is expected to move out as the accretion rate decreases, with radii as large as thousands of km (an advection dominated flow region is supposed to form inside this radius), so that if the break frequency is identified with the Keplerian frequency at this radius, this would be in accordance with the observed correlation. The 40–145 keV X-ray spectrum becomes steeper and the flux in that range weaker as the break frequency increases; it would be of great interest to see what such models predict in this respect.

5. Conclusion

The picture that emerges from our comparison of the EXOSAT data of GX 339–4 to data on other black hole candidates is one in which BHC's move from the low state via an intermediate state to the high state as the mass accretion rate increases. On this trajectory, as a function of $\dot{M}$,

the power spectral break frequency increases and its rms decreases in the way illustrated by Fig 3; the disappearance of the band-limited noise in the HS could be nothing else but the extreme consequence of this process. In the 40–145 keV band the flux drops and the spectrum steepens with $\dot{M}$; at lower energy there is a general increase of the ultrasoft component, but, as has been remarked previously (Tanaka 1992), not in a way that is strictly correlated with the properties of the power law component. We note that the properties of the peculiar flat-topped outburst of GRO 1719-24, with an increasing break frequency (van der Hooft 1996) and at high energy a steepening spectrum and a slightly decreasing flux then suggest that the mass accretion *increased* during the plateau phase of this outburst.

The similarity between the IS and the VHS band limited noise power spectra is remarkable, and it is a major challenge to explain why two such similar states would be separated by one (the HS) with no detectable band limited noise. A clue might be the fact that the VHS power spectra are violently variable, with rapid transitions between a band limited noise and a weak power law power spectrum (Miyamoto et al. 1991).

Note. When this paper was about to be submitted, we analyzed the recent RXTE data on Cyg X-1 in the "high" state (Belloni, Mendez, van der Klis et al. 1996, submitted to ApJ Lett.). We found its properties to be entirely compatible with that of the intermediate state discussed here, which means that there are now three black hole candidates that have shown these properties.

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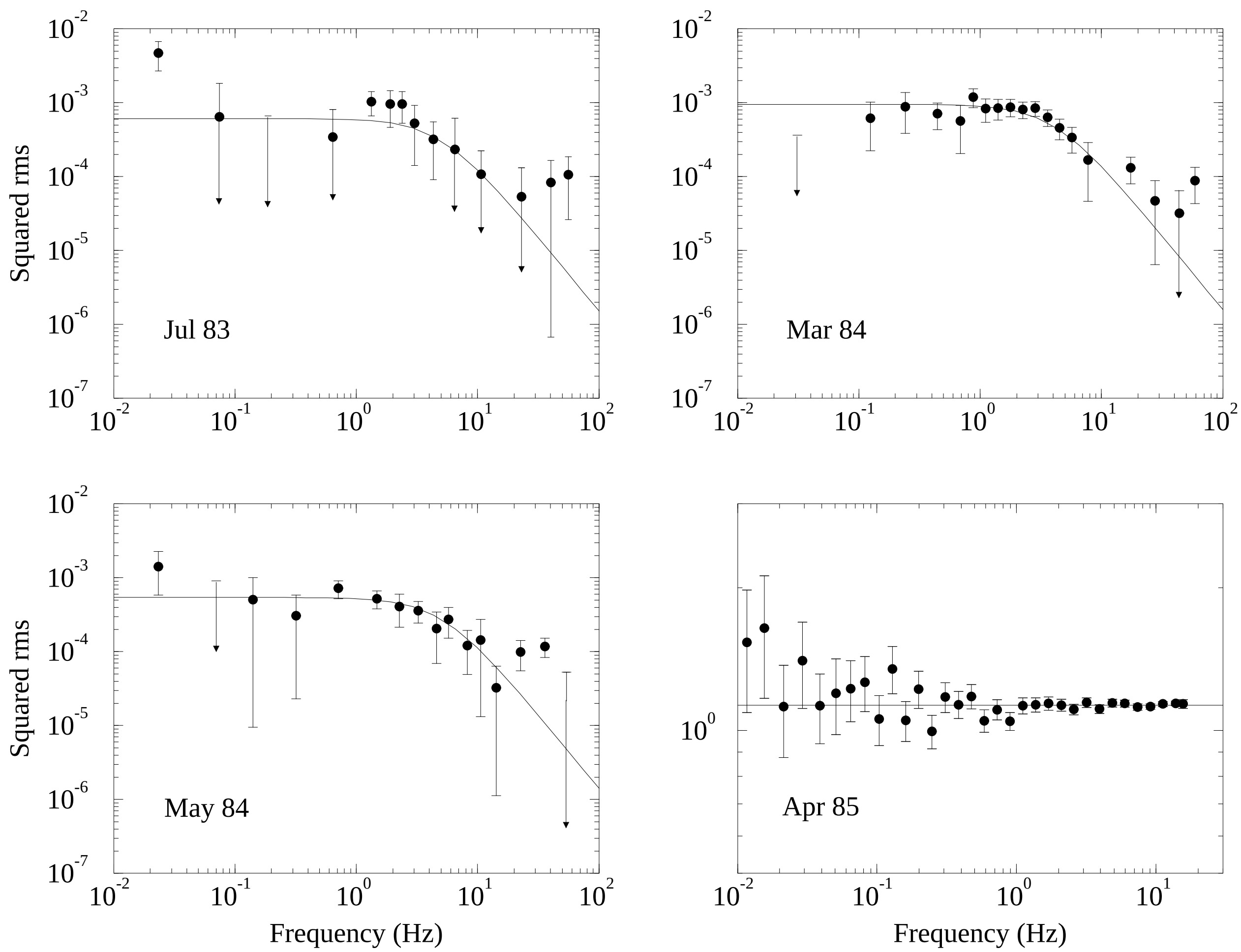

Fig. 1.— The power spectra of GX 339–4. (a) July 1983, (b) March 1984, (c) May 1984, (d) April 1985.

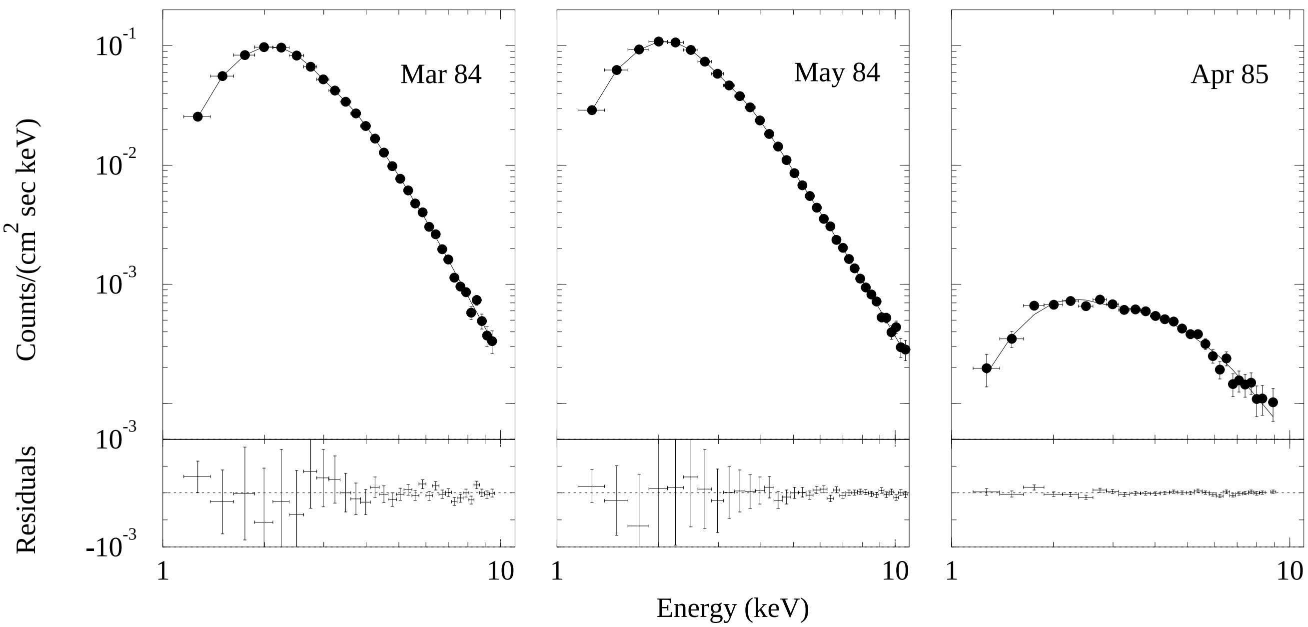

Fig. 2.— The X-ray spectra of GX 339–4. (a) March 1984, (b) May 1984, (c) April 1984.

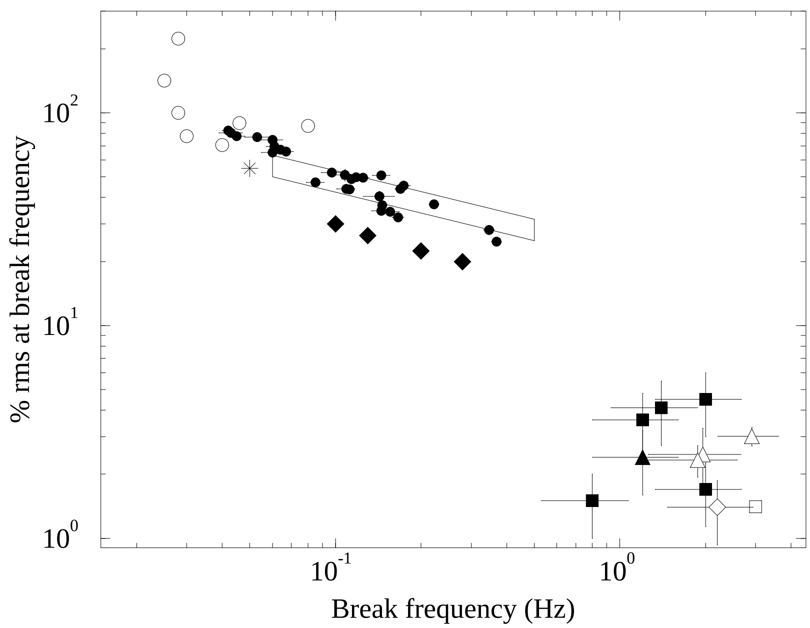

Fig. 3.— Relation between break frequency and power density at the break. Filled circles: Cyg X–1 in the LS (Belloni & Hasinger 1990a); filled diamonds: GRO J1719–24 (van der Hooft et al. 1996); asterisk: GRO J0422+32 (Grove et al. 1994); open circles: GS 2023+338 in the LS (Oosterbroek 1995); filled squares: GX 339–4 in the VHS (Miyamoto et al. 1991, 1993); open diamond: GS 1124–68 in the VHS (Miyamoto et al. 1993); filled triangle: GX 339–4 (Belloni & Hasinger 1990b); open square: GS 1124–68 in the IS (Belloni et al. 1996a); open triangles: GX 339–4 in the IS (this paper). The region marked in this figure corresponds to Cyg X–1 LS data from Crary et al. 1996).